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Arrival of extremely volatile-rich high-Mg magmas changes explosivity of Mount Etna

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ABSTRACT

The volcanic hazard potential of Mount Etna volcano is presently nourished by long-lasting, powerful eruptions of basaltic magmas coupled with increased seismicity

and ground deformation, and the world's largest discharge of volcanic gases. The current evolutionary cycle of Mount Etna activity is consistent with subduction-related chemical modifications of the mantle source. Arrival of a new mantle-derived magma batch beneath the volcano has been hypothesized, but is still elusive among the erupted products. Here we demonstrate petrological and geochemical affinities between the magmas supplying modern eruptions and high-Mg, fall-stratified ("FS") basalts ejected violently ~4 Kyr ago. The "FS" primitive magmas (~13 wt% MgO) are characteristically volatile-enriched (at least 3.8 wt% H_2O and 3300 ppm CO_2), and bear trace element signature of a garnet-bearing, metasomatised source (high Gd/Yb, K/La, U/Nb, Pb/Ce, Ca/Al). They started crystallizing olivine (Fo91), clinopyroxene (Mg# 92.5) and Cr-spinel deep in the plumbing system (> 5 kb), contributing to the cumulate piles at depth and to differentiated alkaline basalt and trachybasalt magmas in the shallow conduit. Continuous influx of mantle-derived, volatile-rich magmas, such as those that supplied the "FS" fallout, provides a good explanation for major compositional and eruptive features of Mount Etna.

Keywords: Etna, volcano, picrite, melt inclusions, volatiles, degassing, mantle, metasomatism.

INTRODUCTION

Mount Etna, positioned at the destructive margin marking the complex collision zone between the African and European plates (Gueguen et al., 1998), is the largest volcano in Europe and one of the most active in the world. The present edifice of Mt. Etna was constructed with fractionation products of mantle-derived magmas, starting ~0.5 Ma ago with eruption of tholeiitic lavas, followed by transitional lavas, eventually

trending to SiO_2-undersaturated, alkaline basalts with distinct trace element and isotope signatures (Armienti et al., 2004; Corsaro and Pompilio, 2004; Tanguy et al., 1997). The compositional changes of the Mt. Etna magmatic system were temporally and genetically linked to continuous modifications in the mantle/lithospheric source(s), caused by metasomatic enrichment in volatiles and incompatible trace elements, and melting-related depletion in basaltic components (Kamenetsky and Clocchiatti, 1996). Dramatic changes in both the source composition and the volcano's eruptive dynamics have been tentatively ascribed to modification of the adjacent subduction system (Schiano et al., 2001; Tonarini et al., 2001), driven by vertical asthenospheric flow in response to the roll-back of the subducting Ionian slab (Doglioni et al., 2001; Gvirtzman and Nur, 1999).

From a historical perspective, Mt. Etna shows increasing activity in recent times, with the frequency of explosive (doubled since the "Fall Stratified" (FS) eruption of high-magnesian magmas ~4 Kyr ago) and effusive eruptions increasing significantly (Coltelli et al., 2000). More recently, since the early 1970s, the magmatic output of Mt. Etna has increased by a factor of four, and more than 120 eruptions have been recorded in the past 20 yr (Branca and Del Carlo, 2005). Notably, the erupted magmas have become more potassic and richer in ^{87}Sr and ^{11}B (Armienti et al., 2004; Clocchiatti et al., 1988; Tanguy et al., 1997; Tonarini et al., 2001), and have been accompanied by enormous output of volcanic gases CO_2, SO_2 and halogens (Allard, 1997; Allard et al., 1991; D'Alessandro et al., 1997). Although, the present day magmas are increasingly magnesian and volatile-rich (Clocchiatti et al., 2004; Corsaro and Pompilio, 2004; Métrich et al., 2004; Spilliaert et al., 2006), and their radiogenic and stable isotope compositions require a mantle origin (Allard et al., 1991; Armienti et al., 2004; D'Alessandro et al., 1997; Marty et al., 1994;

Tonarini et al., 2001), their MgO (< 8.2 wt%) and Ni (< 50 ppm) contents, and forsterite contents of olivine phenocrysts (< 84 mol% Fo) are too low to have been in equilibrium with a typical peridotite mantle.

On the other hand, the indications of a primitive melt entering the plumbing system of Mt. Etna from a mantle reservoir are explicit. In addition to the isotope systematics, these include records of large piles of mafic cumulates extending to depths of 18 km beneath the volcano (De Gori et al., 2005) and the "excessive" (compared to amounts degassed from the erupted magmas) supply of volatiles to the volcanic clouds (Allard et al., 1991; D'Alessandro et al., 1997). As primitive magmas have rarely been ejected in the eruptive history of Mt. Etna (Corsaro and Pompilio, 2004) and have not reached the surface since the "FS" eruption, we used the latter to elucidate controls on recent and current volcanic activity.

"FS" ERUPTION: ROCKS, MINERALS AND MELT INCLUSIONS

The 3930 ± 60 BP (^{14}C age; Coltelli et al., 2000) "FS" eruption produced a pyroclastic fallout deposit of 0.183 km^3 covering the entire eastern flanks of Mt. Etna (Coltelli et al., 2005). The deposit reaches 110 cm in thickness at ~7 km from the summit craters, and its thickness and dispersal indicate that the eruption column reached significant heights (18–20 km (Coltelli et al., 2005)), and thus had high explosive (subplinian) energy. The erupted products are a highly vesiculated (30–60 vol%) scoria lapilli containing euhedral crystals of olivine (< 8%), clinopyroxene (< 3%) and Cr-spinel (< 0.1%). Despite relatively low amounts of ferromagnesian phenocrysts the rocks are high-Mg basalt to picrite in composition (12–17 wt% MgO; Table DR1 of the GSA Data Repository[1]) with high Ni and Cr abundances (135–285 and 920–1330 ppm,

respectively), characteristic of primitive, unfractionated magmas. The rocks are extremely enriched in CaO relatively to Al_2O_3 (CaO/Al_2O_3 = 1.1–1.2) despite the low modal abundances of clinopyroxene phenocrysts. The "FS" rocks are depleted in heavy rare earth elements (HREE) and high-field strength elements (HFSE) relative to REE of higher and similar incompatibility, respectively (Fig. 1). They are also relatively enriched in large-ion lithophile elements (LILE – K and Sr) and Pb (Fig. 1). Depletions and enrichments demonstrated by the ratios of similarly incompatible elements (e.g., K/La, Nb/U, Ce/Pb, Ti/Gd) are typical of subduction-related magmas and commonly attributed to selective addition of LILE> LREE > HFSE to a mantle peridotite by melts and/or fluids derived from a subducting crust. High Gd/Yb in the magmas can be taken as evidence of residual garnet in the source.

High-Mg compositions of the "FS" olivine phenocrysts (Fo 90–91 mol% in the majority of crystals) and clinopyroxene (Mg# 96–92.5) also point to the primitive nature of their parental magmas (see GSA Data Repository). Early crystallization of "FS" clinopyroxene, confirmed by the occurrence of clinopyroxene inclusions in most forsteritic olivine may reflect high Ca abundance in the parental magma and high-pressure crystallization conditions (Grove et al., 1992). Spinel microphenocrysts and inclusions in olivine have extremely high-Cr (Cr# 70–80 mol%) and moderately low-Ti (0.6–1.0 wt% TiO_2) compositions that are also typical of many primitive alkaline island arc magmas, including those from nearby Vulcano, Aeolian arc (Kamenetsky and Clocchiatti, 1996; Kamenetsky et al., 2001).

Olivine-hosted melt inclusions, analyzed for major, trace and volatile elements, using different microbeam techniques, and subsequently corrected for post-entrapment

modifications (see GSA Data Repository for the details of analytical methods and calculations) provide more insight into the nature of the "FS" parental magmas. Melt inclusions (up to 250 μm in size) have negative-crystal shape with scalloped edges and appear as brownish glass with a spherical vapor bubble (Fig. 3), which is sometimes larger than typical shrinkage bubbles (i.e., > 5 vol%). The bubble walls are invariably lined with tiny Ca-Mg carbonate crystals (Fig. 3).

Melt inclusion compositions (after correction for minor post-entrapment modifications; see GSA Data Repository) show a limited range in MgO (12.6±0.3 wt%) and match the bulk rock major and trace element compositions (Fig. 1, 2). Thus, the melt inclusions support our conclusions about high-Mg and high-Ca compositions of the "FS" parental melt with the trace element systematics reminiscent of subduction-related magmatism. Although the average composition of melt inclusions is indistinguishable from the average bulk rock composition, the observed chemical variability among individual inclusions, especially in trace elements (Fig. 1, 2), is very large and cannot be induced by crystallization as the compositions of host olivine grains are similar.

Melt inclusions have moderately high Cl and S (average 0.15 and 0.17 wt%, respectively), but are exceptionally enriched in H_2O and CO_2 for basaltic melts, in general, and primitive, high-Mg basalt, in particular (Fig. 3). The original CO_2 content of trapped melts was undoubtedly higher than measured in glasses, because carbon present in the bubbles (gaseous phase and carbonates) is not quantified. Importantly, H_2O does not correlate with elements of similar incompatibility (see large variability in trace elements in Fig. 2), and thus the effects of degassing cannot be excluded. Nevertheless,

the highest measured abundances of dissolved volatiles indicate very deep crystallization (at least 400–500 MPa, Fig. 3) of clinopyroxene and olivine from the "FS" parental melt.

IMPLICATIONS FOR MODERN ERUPTIONS

The evolution of the "FS" parental melt upon decompression, cooling, degassing and extensive (50%–60%) crystallization of olivine and clinopyroxene (with the plagioclase liquidus depressed by high H_2O contents) can hypothetically account for the compositions of modern lavas at Mt. Etna. The latter show the compositional trends in major and trace elements that can be tracked back to the "FS" compositions (Fig. 2), the geochemical signature consistent with their derivation from the high-magnesian, "FS"-type magma (Fig. 1). Water and CO_2 contents in the melt inclusions of modern eruptions (Del Carlo and Pompilio, 2004; Métrich et al., 2004; Métrich and Rutherford, 1998; Spilliaert et al., 2006) also point to the volatile-enriched character of parental magmas (Fig. 3), however linking the "FS" magmas and the present day magmas requires a more comprehensive interpretation of the behavior of volatile elements. Quantitative relationships between the "FS" and modern magmas are hampered by current lack of relevant experimental data to model the olivine-clinopyroxene cotectic, and undefined extents of primitive magma replenishment, interaction with earlier cumulates, mixing with evolved magmas in the conduit and degassing.

In historic times, and most evident recently, Mt. Etna showed prominent geochemical changes in the erupted products (Armienti et al., 2004; Clocchiatti et al., 1988; Tanguy et al., 1997; Tonarini et al., 2001) and dramatically increased volcanic activity, seismicity and ground deformation (Branca and Del Carlo, 2005; Patane et al., 2003). Uncommon elsewhere in the world, frequent explosive eruptions of basaltic

magmas in the latest volcanic cycles of Mt. Etna are coupled with the largest (for a single volcano) emissions of volcanic gases CO_2 and SO_2 (Allard, 1997; Allard et al., 1991; D'Alessandro et al., 1997). Another unusual aspect of the Mt. Etna magmatic system is the vertical extent (up to 18 km) of the magma storage region and related mafic cumulates advocated by geophysical and geochemical data (Allard, 1997; Chiarabba et al., 2000; De Gori et al., 2005; Laigle et al., 2000; Tanguy et al., 1997). A prerequisite to all features that make present-day Mt. Etna an extraordinary magmatic system is arrival of new primitive magma into the feeding system. Such magma, hypothesized in several works (Clocchiatti et al., 2004; Métrich et al., 2004; Patane et al., 2003; Spilliaert et al., 2006) but not sampled directly among recent volcanics, can be best approximated by an unevolved, mantle-derived "FS"-type magma, established in our study. The "FS"-type melt demonstrates properties critical for positive magma buoyancy; namely, originally high abundances of dissolved H_2O and CO_2 that were further increased by crystallization of olivine and clinopyroxene at depth. Subsequent decompression promoted early saturation of the melt in volatiles, vesiculation, and rapid ascent of the low-density, highly buoyant melt-bubble mixture. Thus, the explosive dynamics of modern Mt. Etna can be related to a deep supply of volatile-rich, high-Mg magmas. The recognition of such magmas in the plumbing system of Mt. Etna is also important in linking shallow-crust and surface processes to the evolution of the mantle source region. The "FS"-type melt provides compelling compositional evidence that Mt. Etna is currently supplied from a source, increasingly fluxed by melts and fluids, in a continuously changing tectonic framework.

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FIGURE CAPTIONS

Figure 1. Primitive mantle normalized (after Sun and McDonough, 1989) trace element compositions of "FS" rocks (open circles, average of 6 samples), melt inclusions hosted in "FS" olivine phenocrysts (closed circles, average of 23 melt inclusions; the bars show one standard deviation), and Mount Etna lavas erupted in 2001–2002 (diamonds, average of 61 samples; after Andronico et al., 2005; Corsaro et al., 2006).

Figure 2. Comparison between the compositions of the "FS" parental magmas (exemplified by recalculated melt inclusions), "FS" whole rocks and modern lavas of Mount Etna (Andronico et al., 2005; Corsaro et al., 2006). Note significant variations in trace elements among individual melt inclusions. Symbols as in Figure 1.

Figure 3. Relationships between H_2O and CO_2 contents in melt inclusions from "FS"olivine (circles), phenocrysts in recent Mount Etna lavas (diamonds; after Métrich et al., 2004; Spilliaert et al., 2006) and arc basalts (dotted outline; after Wallace, 2005). Note that adequate comparison of data from different sources requires normalization to the same degree of fractionation. Isobars are calculated at 1220 °C and 47.5 wt% SiO_2 in melt using VOLATILECALC (Newman and Lowenstern, 2002). Inset shows typical H_2O- and CO_2-rich silicate melt inclusion with a CO_2-vapor bubble in "FS" olivine. The bubble's walls are coated by tiny Ca-Mg-bearing carbonates (determined by laser Raman

spectroscopy, GeoForschungsZentrum Potsdam, Germany), thus the initial CO_2 content was even higher than measured.

[1]GSA Data Repository item 2007xxx, Analytical and calculation methods, Tables DR1, DR2 and DR3, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.